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Oumbe A., Blanc Ph., Schroedter-Homscheidt M., Wald L., 2010. Solar surface irradiance from new meteorological satellite data. In Proceedings of the 29th Symposium of the European Association of Remote Sensing Laboratories, Chania, Greece, 15-18 June 2009. I. Manakos and C. Kalaitzidis (Eds.). Published by IOS Press, 320-328, doi:10.3233/978-1-60750-494-8-320

Solar surface irradiance from new meteorological satellite data

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Abstract. This paper presents the first prototype of a new method, for assessing solar surface irradiance, benefiting from advanced products derived from recent Earth Observation missions. This method -called Heliosat-4- is based on the radiative transfer model libRadtran and will provide direct, diffuse components and spectral distribution of solar surface irradiance every 3 km and ¼ h over Europe and Africa. The advantage of the Heliosat-4 method is the simultaneous computation of direct and diffuse irradiances. The outcomes of this prototype of Heliosat-4 method are compared to ground measurements, of direct and global irradiances, made at 4 stations in Europe and Northern Africa. The results show that standard deviation attained by the Heliosat-4 method for global irradiance is fairly similar to that attained by current methods. A significant bias is actually observed and discussed.

Keywords. Atmospheric optics, radiative transfer, solar irradiance, cloud, MSG, Envisat, MetOp.

Nomenclature

z, z_0, z_H	altitude (km) above mean sea level
I_0	irradiance at the top of the atmosphere (W m^{-2})
I, I_B, I_D	global, direct, diffuse irradiance on horizontal plane (W m^{-2})
$I^{clearsky}$, $I_B^{clearsky}$	global, direct irradiance on horizontal plane under clear sky (W m^{-2})
$T_{cloud+albedo}$	cloud extinction and ground albedo contribution (unitless)
$A(z)$, $A_B(z)$	attenuation coefficients of the atmosphere for global, direct irradiance (unitless)
α, α_B	parameters of the double-*z* fitting function (m^{-1})
ρ	ground albedo (unitless)
ρ_{sph}, ρ_{sph}'	spherical albedo for clear and cloudy sky (unitless)
a, b	empirical parameters for modified Lambert-Beer relation (unitless)
τ_0, τ_{0B}	optical depths for modified Lambert-Beer relation (unitless)
τ_c	cloud optical depth (unitless)
$\tau_{aer550nm}$	aerosol optical depth at 550 nm (unitless)
α	Angstrom coefficient (unitless). It characterizes spectral variation of aerosol optical depth
vis	visibility at ground level (km)
θ_s	solar zenith angle (°)

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1. INTRODUCTION

Accurate estimating of solar surface irradiance (SSI) is necessary for an efficient planning and harnessing solar energy to produce electricity or heat. It is also important to assess the radiative forcing of the climate system. SSI has been for long estimated from measurements made within meteorological stations networks [1]. However, such networks do not offer a dense nor sufficient coverage to provide an accurate description of spatial variations of the resource. As an alternative, several methods have been developed in the past years to assess the SSI from images taken by satellites [2]. Most current methods are inverse, *i.e.* the inputs are satellite images whose digital counts result from the ensemble of interactions of radiation with the atmosphere and the ground during the downward and upward paths of the radiation. The authors believe from experience that limits of such methods are presently reached in terms of accuracy, except for those are specialized to a specific region using empirical fittings. Consequently, a new paradigm is studied based on a direct modeling. This would permit to deliver knowledge on direct, diffuse components and spectral distribution, which is seldom offered by current methods.

Recent satellite missions such as Meteosat Second Generation, Envisat and MetOp combined with recent data assimilation techniques into atmospheric modeling offer a favorable context for the design and exploitation of a method based on a direct modeling. In this approach, the various optical processes occurring along the path of the light from the outer space towards the ground are modeled by the means of a radiative transfer model (RTM).

In this work, we propose a prototype of a direct method – called Heliosat-4 – for assessing the SSI; it exploits advanced products derived from recent satellite data and is based on a radiative transfer model. Our final goal is to integrate it into an operational system for providing operationally direct and diffuse components and spectral distribution of the SSI for the usable Meteosat image pixels (9 million pixels, 3 km resolution at nadir of the satellite and each quarter-hour). This SSI data will be disseminated by the means of the SoDa Service (www.soda-is.com) [3]. This communication deals with the SSI integrated over the spectral interval [0.3 µm, 4 µm].

2. METHOD

2.1. Background

The Heliosat-4 method is under joint development by the DLR (German Aerospace Center) and MINES ParisTech. The libRadtran RTM has been selected for this development. libRadtran was originally developed for modelling UV irradiance. Its accuracy has also been demonstrated for actinic fluxes and total irradiance (www.libradtran.org) [4].

There are many inputs to RTMs. [5] performed an inventory of the variables (e.g., cloud) and their attributes (e.g., optical depth) available in an operational mode and assessed to which degree the uncertainty on an attribute of a variable –including the absence of value– leads to a variation on the SSI. They found a number of significant inputs:

- solar zenith angle (θ_s) and number of the day in the year,
- cloud optical depth (τ_c),

- cloud type,
- water vapor amount,
- aerosol optical depth and its spectral variation ($\tau_{aer550nm}$, α),
- aerosol type,
- ground albedo (ρ) and its spectral variation,
- atmospheric profile,
- ground altitude (z).

Another result of this sensitivity analysis is that the influences of vertical position and the geometrical thickness of clouds in the atmosphere are negligible. Thus, the SSI I for a cloudy atmosphere can be considered as equal to the product of the irradiance obtained under a clear sky ($I^{clearsky}$) and a function of the cloud extinction and ground albedo contribution ($T_{cloud+albedo}$):

$$I \approx I^{clearsky} \quad T_{cloud+albedo} \tag{1}$$

2.2. Scheme

For our objectives, look-up tables can be used. The look-up tables are cumbersome to compute and then to implement in the routine operations. If new descriptions of atmospheric properties are available, the look-up tables should be recomputed for the new conditions and re-implemented in the processing software. They have the advantage of making the subsequent operations much faster. Here, we have opted for another approach by using libRadtran and a combination of simpler approached models that run fast enough for our purposes.

Considering Eq. 1 and taking into account that *i)* the variations with the altitude z of the term $T_{cloud+albedo}$ are negligible and *ii)* the cloud parameters may be known in an operational mode every ¼ h and 3 km and *iii)* the clear-sky parameters only every day and 50 km, the concept of the Heliosat-4 method is that the SSI I can be computed by the products of three models as follows:

$$I = \underset{\text{daily and 50 km}}{I^{clearsky}} \quad f(z) \quad \underset{\text{¼ h and 3 km}}{T_{cloud+albedo}} \tag{2}$$

where each model differs from the others with respect to space and time scales. The first model computes the clear-sky irradiance $I^{clearsky}$; it takes into account all atmospheric parameters but clouds and ground albedo and focuses the bulk of computation resources. The second model $f(z)$ corrects for ground elevation for a given site and the third model take into account the clouds extinction and the contribution of the ground albedo to the SSI ($T_{cloud+albedo}$). The second and third models are much simpler and run faster than the first one. A sketch of the scheme is given in Fig. 1.

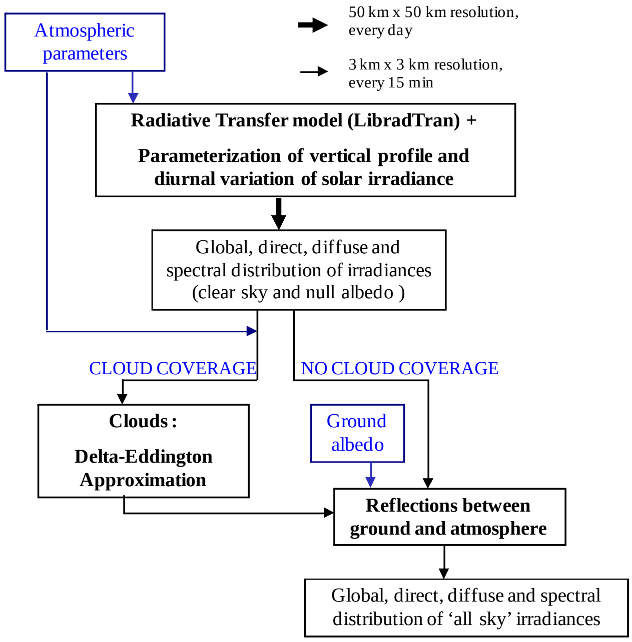

Figure 1. Heliosat-4 scheme

2.3. The clear-sky part of the scheme

The Heliosat-4 method exploits a clear-sky model which is in this case the RTM libRadtran combined with the modified Lambert-Beer (MLB) relation proposed by [4]. The MLB relation is a fitting function modelling the influence of the solar zenith angle in order to save computing time:

$$I^{clearsky}(\theta_s) = I_0 \exp(-\tau_0 / \cos^a \theta_s) \quad (3)$$
$$I_B^{clearsky}(\theta s) = I_0 \exp(-\tau_{0B} / \cos^b \theta_s)$$

where τ_0, τ_{0B} and a, b are determined from the knowledge of the global and direct irradiances at solar zenith angles equal to 0° and 60°. This knowledge is obtained by two runs of libRadtran.

Inputs to libRadtran are the optical depth and type of the aerosols, the water vapour and ozone content, which are themselves assessed from data provided by the satellites Envisat and MetOp [6] [7]. These inputs are provided for cells of 50 km in size.

2.4. Double-z fitting function for vertical profile of irradiance

The mean terrain altitude for each cell, z_0, is also an input to libRadtran. The altitude of the terrain has a large influence on the irradiance and it is necessary to take into account the actual altitude of the site of interest in the assessment of the clear-sky irradiance and consequently of the SSI. It would be too time-consuming to run libRadtran for each altitude. Given the fact that libRadtran can run with two altitudes (z_0 and z_H) as inputs in one call, we have designed the use of the double-z fitting function described below to perform the altitude correction. Knowing values of clearsky irradiances at two different altitudes $I^{clearsky}(z_H)$ at z_H and $I^{clearsky}(z_0)$ at z_0, this fitting function allows to determine clear-sky irradiances at other altitudes. It is called "double-z fitting function" because it needs as inputs the clear-sky irradiances at two altitudes. The form of this function has been defined from the typical vertical profile of direct irradiance but was then found suitable to the global irradiance, i.e., the sum of the direct and diffuse components :

$$I^{clearsky}(z) = I_0\,(1- A(z_0)\,exp[-\alpha(z - z_0)]) \qquad (4)$$
$$I_B^{\ clearsky}(z) = I_0\,(1- A_B(z_0)\,exp[-\alpha_B(z - z_0)])$$

$A(z_0)$ and α can then be computed as:

$$A(z_0) = 1 - (I^{clearsky}(z_0) / I_0) \qquad (5)$$
$$\alpha = -ln[(I_0 - I^{clearsky}(z_H))/(I_0 - I^{clearsky}(z_0))] / (z_H - z_0)$$

The same equations hold for $A_B(z_0)$ and α_B, where $I_B^{\ clearsky}(z_H)$ and $I_B^{\ clearsky}(z_0)$ are the direct clear-sky irradiances at z_H and $z_{0.}$ z_H has been empirically defined to obtain the best results for elevations between 0 and 8 km and is set to, in km:

$$z_H = max(3, z_0 +2) \qquad (6)$$

The double-z fitting function is well described in [8].

2.5. Clouds extinction and ground albedo contribution

Since the geometrical thickness of clouds has a negligible effect on the SSI, it is set up to a fixed value of 1 km. Then, we assume that the irradiance passing through the clouds is divided into downward and upward irradiances. Therefore, we use the well-known two-stream and delta-eddington approximations [9] to model the extinction due to clouds:

$$I_B = I_B^{\ clearsky}\ exp(-\tau_c / cos\theta_s) \qquad (7)$$
$$I_D = t_D\,(I_D^{\ clearsky} + R_c\,\rho_{sph}) + (t_B - t_D)\,I_B^{\ clearsky}$$

where R_c is the irradiance reflected by the cloud and is given by:

$$R_c = (r_D\,I_D^{\ clearsky} + r_B\,I_B^{\ clearsky}) / (1 - r_D\,\rho_{sph}) \quad (8)$$

The effective diffuse and the direct-to-diffuse transmissivities and reflectivities – respectively $r_{D,}$ t_D and $r_{B,}$ t_B– are determined from the radiation boundary conditions (Paris and Justus, 1988). The spherical albedo ρ_{sph} is computed previously in the clear-sky part of the scheme.

If we consider that an infinite series of reflection and scattering takes place between the ground and the atmosphere, the SSI computed for a null ground albedo can be corrected for the actual ground albedo ρ:

$$I(\rho) = I(\rho=0) / (1 - \rho\,\rho_{sph}') \qquad (9)$$

where ρ_{sph}' is the spherical albedo for the cloudy atmosphere. The input to the cloudy part of the scheme is the cloud optical thickness derived from an appropriate processing of the Meteosat images made at DLR. Presently, the ground albedo is set arbitrarily; a database should be found for operation.

3. COMPARISON BETWEEN RESULTS AND STATION MEASUREMENTS

We have applied the Heliosat-4 method to data provided by the DLR (clouds, water vapour, aerosols) and EUMETSAT (ground albedo) for the year 2004. Values of irradiance for every quarter-hour were averaged to yield hourly means of irradiance, with is the time resolution of ground measurements. These assessed SSI are compared to measurements performed by pyranometers at four meteorological stations, where global and direct measurements were available (Table 1). The ground data are provided by MESoR (www.mesor.org). We only use measurements with direct irradiance greater than 10 W m^{-2}. For lower values, the measured irradiance is mainly of diffuse nature and is influenced by local conditions, including orography and the presence of nearby obstacles. By removing these values, we ensure better conditions for understanding the results at this preliminary stage. For the same reason, we avoid measurements taken at solar zenith angle greater than 70°. Above this angle, atmospheric parameters are not well estimated.

Site	Station	Country	Latitude / Longitude(°)	Altitude (m)
1	Freiburg	Germany	48.04 / 7.87	241
2	Payerne	Switzerland	46.81 / 6.94	492
3	Tamanrasset	Algeria	22.78 / 5.51	1368
4	Vaulx-en-Velin	France	45.78 / 4.93	173

Table 1. Stations used for validation

The discrepancies between the estimated and measured and SSI are assessed. Table 2 displays the mean value of the SSI measured at ground level, the bias, i.e., the mean difference, the standard deviation and the correlation coefficient between the two series of values. The bias is positive for all sites. This means that, in general, the method over-estimates the SSI. The bias may be low as in the case of Tamanrasset (station 3) or high as in the case of Vaulx-en-Velin (station 4). The correlation coefficient is high in all cases: the temporal variation in radiation is well reproduced by the Heliosat-4 method. For global irradiance, the standard deviation ranges from 60 W m^{-2} to 100 W m^{-2}; in relative values it is closed to 20 % in all cases, except for Tamanrasset for which it is 9 %. The discrepancies are higher for direct irradiance than for global irradiance. Therefore, errors seem to come from the estimation of direct irradiance.

Site	Num	Mean (W m^{-2})	Bias (W m^{-2})	Std (W m^{-2})	Corr
1 - global	**550**	**487**	**87 (18 %)**	**94 (19%)**	**0.905**
1 - direct	550	282	101 (36 %)	135 (48 %)	0.803
2 - global	**1628**	**516**	**61 (12 %)**	**85 (16 %)**	**0.927**
2 - direct	1628	330	76 (23 %)	117 (36 %)	0.869
3 - global	**2352**	**658**	**39 (6 %)**	**61 (9 %)**	**0.975**
3 - direct	2352	471	75 (16 %)	119 (25 %)	0.896
4 - global	**1320**	**513**	**84 (16 %)**	**101 (20 %)**	**0.896**
4 - direct	1320	330	88 (27 %)	130 (40 %)	0.837

Table 2. Performance of Heliosat-4 for global and direct SSI. Std means standard deviation, *Num* is the number of observations and *Corr* means correlation coefficient.

We consider that an important part of bias comes from clear sky. For example, in Vaulx-en-Velin, 52 % of the cases where the relative deviation on the direct irradiance are higher than 10 % are obtained with null cloud optical depth (cloud optical depth is null for 54 % of observations in Vaulx-en-Velin). Since the same clear sky model is used for clear and all skies, we evaluated the quality of the clear sky model of Heliosat-4 (Table 3). Thus, we focused on clear skies situations. The clear sky conditions we chose are clear sky index greater than 0.9 and cloud optical depth null. Since the radiative transfer model libRadtran were used as reference for the design of Heliosat-4, we do same validations with libRadtran outputs (Table 4).

Site	Num	Mean (W m^{-2})	Bias (W m^{-2})	Std (W m^{-2})	Corr
1 - global	**163**	**580**	**36 (7 %)**	**28 (5 %)**	**0,993**
1 - direct	163	470	23 (5 %)	57 (12 %)	0,962
2 - global	**674**	**614**	**24 (4 %)**	**30 (5 %)**	**0,991**
2 - direct	674	496	23 (5 %)	47 (10 %)	0,972
3 - global	**1649**	**721**	**30 (4 %)**	**36 (5 %)**	**0,991**
3 - direct	1649	570	53 (9 %)	80 (14 %)	0,939
4 - global	**505**	**631**	**40 (6 %)**	**47 (7 %)**	**0,979**
4 - direct	505	515	33 (6 %)	62 (12 %)	0,950

Table 3. Performance of Heliosat-4 on clear skies situations for global and direct SSI. Std means standard deviation, Num is the number of observations and Corr means correlation coefficient.

Site	Num	Mean (W m^{-2})	Bias (W m^{-2})	Std (W m^{-2})	Corr
1 - global	**163**	**580**	**49 (8 %)**	**23 (4 %)**	**0,995**
1 - direct	163	470	26 (5 %)	53 (11 %)	0,967
2 - global	**674**	**614**	**46 (7 %)**	**24 (4 %)**	**0,994**
2 - direct	674	496	37 (7 %)	42 (9 %)	0,977
3 - global	**1649**	**721**	**49 (7 %)**	**28 (4 %)**	**0,995**
3 - direct	1649	570	65 (11 %)	77 (13 %)	0,943
4 - global	**505**	**631**	**55 (9 %)**	**36 (6 %)**	**0,987**
4 - direct	505	515	39 (8 %)	56 (11 %)	0,957

Table 4. Same as Table 3, but for libRadtran.

Tables 3 and 4 show that, for the same inputs, in clear skies, Heliosat-4 and libRadtran performances are similar. These tables also show an important bias comparing to ground measurements. The bias on clear skies have a significant effect on all skies: the greater the clear sky bias, the greater the all sky bias. For Vaulx-en-Velin (site 4), reducing clear sky irradiance of 6 %, *i.e.* clear sky bias for site 4, induces a decrease of all sky bias from 16 % (global) and 27 % (direct) to 8 % (global) and 17 % (direct), with a small decrease of standard deviation. These biases may come from inputs data. Data availability of the clear sky parameters (water vapour and aerosol loading) is fairly low. We are using one value per day for a 50 km pixel. The error induced on the SSI depends on the variation of these parameters within the pixel. Comparisons of ground measurements of hourly means of SSI made at sites in Europe less than 50 km apart for clear skies show that the spatial variation in SSI, expressed as the relative root mean square difference, can be greater than 10 %.This result is in agreement with [10] who stressed the large spatial variability of the SSI.

4. CONCLUSION

Compared to current methods [2] the Heliosat-4 method should not only produce total global irradiance, but also direct and diffuse components, and spectral distribution. First results show that the standard deviation on global irradiance attained by the Heliosat-4 method is similar to that attained by current methods. These tests are very encouraging. A strong drawback is the overestimation of both global and direct irradiances. Several causes may be invoked: the lack of temporal and spatial resolution of clear sky parameters, and the aerosol type and the spectral variation of the aerosol optical depth that are not taken into account as we used only $\tau_{aer550nm}$. It is also believed that a better modeling of the cloud extinction can be done if cloud effective radii are known with subsequent more accurate assessments. This first prototype of the Heliosat-4 method shows promises. It demonstrates that principles are sound. There is space for improvements and the authors are confident that the Heliosat-4 method will reach a satisfactory quality.

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